Nonlinear Modeling, Analysis and Design of an Active Antenna in S Frequency Band

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ABSTRACT

An active antenna for transmitter application in S frequency band is designed and analyzed using harmonic balance technique which is based on the nonlinear model of active devices. In this active antenna, the amplifier is integrated with the radiator which is a rectangular patch antenna. This patch antenna is analyzed employing full-wave momentum method. By applying nonlinear model of transistor in the amplifier and separating the linear and nonlinear parts, the harmonic balance equation is obtained. The splitting algorithm is applied to solve the harmonic balance equation and obtain the steady-state voltages at common port. The results of this method are compared with those of commercial simulators.

KEYWORDS

Active antenna, nonlinear analysis, nonlinear circuits, full wave analysis, microstrip antenna.

1. INTRODUCTION

In recent years, active microstrip antennas have become an area of growing interest because they can reduce size, weight and cost of the transmitter and receiver systems [1]. Current researches on active microstrip antennas can be classified into two main groups: oscillator-type and amplifier-type active antennas. The oscillating active antenna is often used to transmit the signal or provide power combining elements [2], [3]. The amplifier–type active antenna, in which the amplifier is integrated with microstrip patch, has been an important topic in the recent researches [4], [5]. It has been shown that in addition to the advantages of reducing the losses in the feed circuits, this type of active antenna can be designed with a higher gain and a wider gain bandwidth compared to the passive antenna. Also, the simulation routine of nonlinear active circuits is the harmonic balance approach which is a powerful method and has been used for analyzing different kinds of nonlinear circuits such as voltage control oscillators and receiving active antennas [6]-[7].

In our research, we first design an amplifier-type active antenna, in which the antenna is a rectangular patch. This passive antenna is analyzed by the Momentum simulator. Then we use the harmonic balance approach for analyzing this active antenna to obtain the steady state responses of the whole circuit. The obtained results using this approach and simulation with commercial software are both shown.

The rest of the paper is organized as following. Section 2 contains a brief review on nonlinear model of MESFETs. The proposed circuit design and its analysis approach and obtained results are given in the next two sections. At last, the paper ends with a conclusion in section 5.

2. NONLINEAR MESFET MODEL

It is obvious that better and more accurate design and analysis of microwave circuits can be obtained by choosing suitable model for linear and nonlinear elements. For analyzing circuits in which FET transistors are used in voltage level beyond the linear region, we should use a nonlinear FET model. Fig. 1 shows a typical nonlinear model of a MESFET.

In circuit simulation and design, in order to prevent complex calculations, we can neglect a number of elements such as diodes, so the nonlinear elements of the model are limited to C_{gs} and C_{gd} capacitors and I_{ds} current source. Among different nonlinear models for MESFET transistors, the Cubic Curtice model is used for the employed transistor in the circuit [8]. Also the gate-drain capacitance is neglected due to its small value. The parameters of Cubic Curtice model are given in Table 1. These parameters have been extracted from mathematical equations of the model elements and the bias point. The drain current relationship with gate-source and drain-source voltage is given by:

$$I_{ds} = I_{ds\,0} \tanh(\mathcal{W}_{ds}) \tag{1}$$

$$I_{ds\,0} = (A_0 + A_1 v_1 + A_2 v_1^2 + A_3 v_1^3) \tag{2}$$

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$$v_1 = V_{gs}(1 + \beta(V_{ds0} - V_{ds})); \qquad V_{ds} \geq 0$$

$$v_1 = V_{gd}(1 + \beta(V_{ds0} + V_{ds})); \qquad V_{ds} < 0 \qquad (3)$$

$$v_2 = (1 + \beta(V_{ds0} + V_{ds})) \qquad (4)$$

$$Q_{gs} = \begin{cases} 2V_{BI}C_{GS0}(1-(1-F_c)^5) + C_{GS0}/(1-F_c)^{1.5}*\theta & V_{gs} \geq F_c V_{BI} \\ \theta = ((1-1.5F_c)(V_{gs} - F_c V_{BI}) + (V_{gs}^2 - (F_c V_{BI})^2)/4V_{BI}) & \\ 2V_{BI}C_{GS0}(1-(1-V_{gs}/V_{BI})^5) & V_{gs} < F_c V_{BI} \end{cases}$$
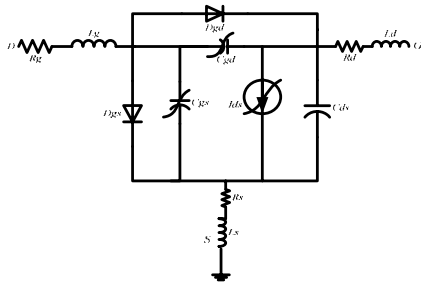
$$(5)$$

Figure 1: Nonlinear model of a MESFET

TABLE 1. CUBIC CURTICE MODEL PARAMETERS

A_0 =0.05841	n =1.5	F_c =0.5	V_{BI} = 0.76 volt
A_1 =0.10341	γ =2.35	β =0.02	V_{ds0} =5 volt
A_2 = -0.0092479	Eg =1.1 volt	C_{gs0} =1.75*10^{-13} F	V_{t0} = -1.2 volt
A_3 = -0.048684	Vbr =12 volt	C_{ds} =4.82*10^{-14} F	R_{in} =2.97 ohm

The device that has been used as the active element of the amplifier is NE3210S01, biased in class A (V_{gs}=-0.48 volt, V_{ds}=2 volt).

3. CIRCUIT DESIGN

A. Amplifier Design

A transmitting active antenna with a single stage amplifier is designed to have good $VSWR_{in}$, $VSWR_{out}$ and flat transducer power gain. The active device in this circuit is NE3210S01 whose small signal scattering parameters are extracted from its datasheet. The calculated stability factor shows that this transistor is unstable in the design band. Thus, in order to stabilize the active circuit, the transistor is loaded with two parallel resistors at both input and output. This active antenna needs two matching networks, which are designed using simultaneous conjugate match conditions ($\Gamma_s = \Gamma_{IN}^*, \Gamma_L = \Gamma_{OUT}^*$) to maximize the transducer power gain (TPG) [9]. It is also assumed that the source and load impedances equal $50\,\Omega$. Using these assumptions, the S_{11} and S_{22} parameters of the amplifier are obtained by simulation and are shown in Fig. 2. In the next section we will compare these
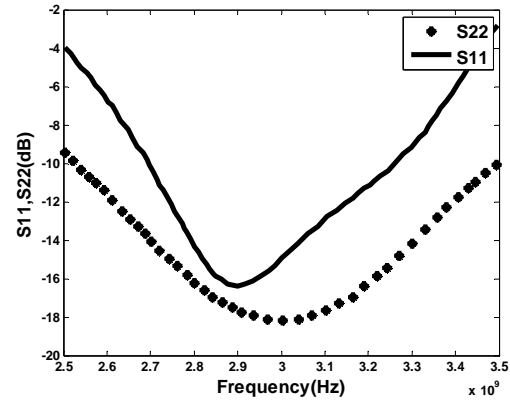
parameters with those of an active antenna.

Figure 2: S_{11} and S_{22} parameters of the designed amplifier

B. Passive Antenna Design

Among different planar antennas such as dipoles, microstrip patches, bowties, or slot antennas which can be used as a radiator in active antenna, we choose microstrip patch because of its low profile, easy fabrication and analysis and its compatibility with solid state devices.

The rectangular microstrip patch antenna, which is used as the load of the amplifier, is designed at a fundamental resonant frequency of 3 GHz [10].

The first design step is to choose suitable dielectric substrate of appropriate thickness. We select RT/duroid 5880. The characteristics of this substrate are given in Table 2.

TABLE 2. PARAMETERS OF THE PATCH ANTENNA

substrate	ε_r	h, mm	t, mm
RT /Duroid	2. 2	1. 588	0.035

For a dielectric of thickness h, and antenna operating frequency of f_r, the practical width is [10]:

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{1+\varepsilon_r}} \qquad (6)$$

where c is the velocity of light. Once W is known, the effective dielectric constant $\varepsilon_{re}(f)$ and the line extension ΔL can be computed from the following relation [11]:

$$u = W/h$$

$$\frac{\Delta L}{h} = 0.412 \frac{(\varepsilon_{re}(f) + 0.3)(W/h + 0.264)}{(\varepsilon_{re}(f) - 0.258)(w/h + 0.8)}$$

$$\varepsilon_{re}(f) = \varepsilon_r - \frac{\varepsilon_r - \varepsilon_{re}}{1 + P(f)}$$

$$P(f) = P_1 P_2 [(0.1844 + P_4 P_3)f_n]^{1.5763}$$

$$P_1 = .27488 + u\left\{0.6315 + 0.525/(1 + 0.0157 f_n)^{20}\right\} - 0.65683 \exp(-8.7513 u)$$

$$P_2 = 0.33622\left\{1 - \exp(-0.03442\,\varepsilon_r)\right\}$$

$$P_3 = 0.0363 \exp(-4.6u)\left\{1 - \exp(-(f_n/38.7)^{4.97})\right\}$$

$$P_4 = 1 + 2.751 \left\{ 1 - \exp \left[- \left(\varepsilon_r / 15.916 \right)^8 \right] \right\}$$

$$f_n = 47.713 \, k_0 h$$

$$\varepsilon_{re} = \frac{1 + \varepsilon_r}{2} + \frac{\varepsilon_r - 1}{2} \left(1 + 10 / u \right)^{-ab}$$

$$a = 1 + 1/49 \ln \left\{ \left(u^4 + \left(u/52 \right)^2 \right) / \left(u^4 + 0.432 \right) \right\}$$
$$+ 1/18.7 \ln \left\{ 1 + \left(u/18.1 \right)^3 \right\}$$

$$b = 0.564 \left(\frac{\varepsilon_r - .9}{\varepsilon_r + 0.3} \right)^{0.053} \tag{7}$$

in which, h is the height of the substrate. The length of the resonant element is then obtained from [10]:

$$L = \frac{c}{2 f_r \sqrt{\varepsilon_e}} - 2 \Delta L \tag{8}$$

We further select a center microstrip feed arrangement [9]. In order to obtain a well matched broadband passive antenna, a matching network is designed at the input port of the patch antenna. The designed patch antenna is simulated with full-wave Momentum simulator, and then the whole passive broadband antenna including its input matching network is simulated.

The overall schematic of the designed passive antenna is shown in Fig. 3. It has a bandwidth of 10% at the level of -7 dB return loss. The obtained input impedance will be considered as a load for the amplifier in harmonic balance analysis.

Integrating the whole passive antenna and the designed amplifier leads to an active antenna whose S_{11} parameter has been improved considerably compared with those of the amplifier alone. Furthermore the active antenna has a bandwidth of 33% (2.467-3.467 GHz) at the level of *VSWR*= 1.5. The overall schematic of the designed active antenna and its S_{11} parameter are shown in Fig. 4 and Fig. 5 and values of its elements are given in Tables 3 and 4.

One of the important points in the active antenna analysis is related to its pattern which has the same shape as the pattern of passive antenna. It means that integrating the amplifier with passive antenna will not change the pattern shape of passive antenna. Pattern of the passive antenna which is obtained with full-wave analysis is shown in Fig. 6. In Fig 6-a, the E field pattern computed in 3 GHz is plotted for $\varphi = 0°$ plane. Also in Fig 6-b the pattern in $\theta = 90°$ is given.
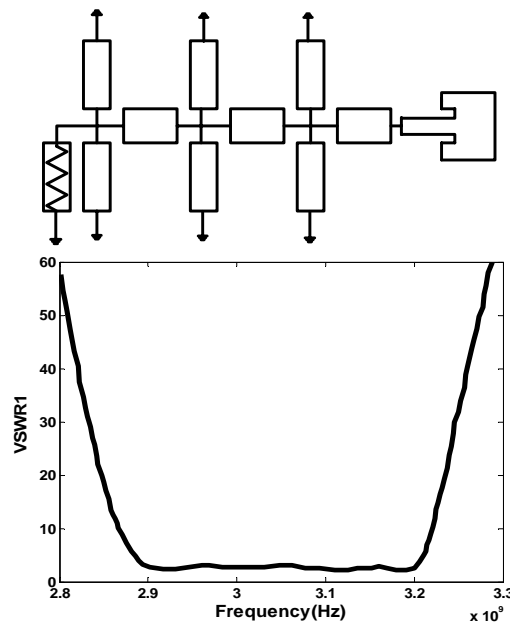
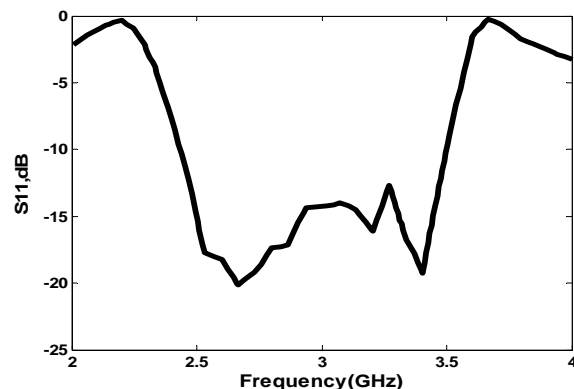

Figure 3: Designed broadband passive antenna and its VSWR

Figure 4: S_{11} parameters of the whole active antenna

TABLE 4: VALUES OF TRANSMISSION LINE PARAMETER

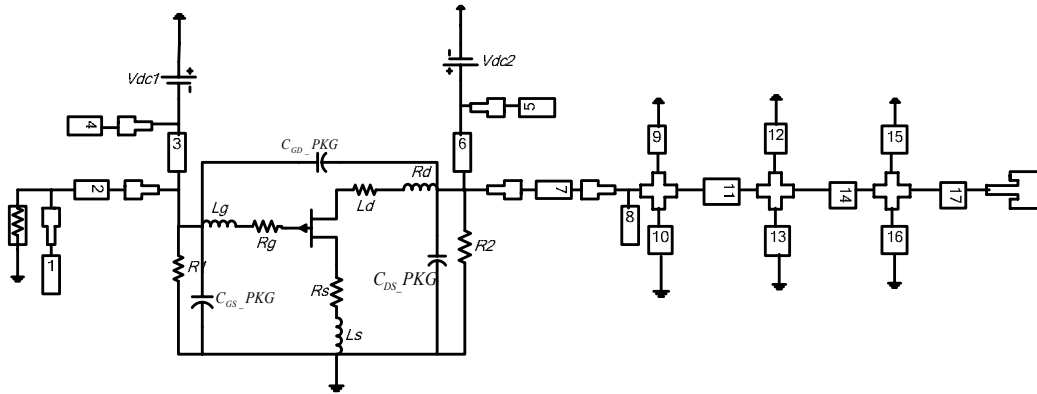|	W(mm)	L(mm)
TL1	1. 5	76.95
TL2	2 .326	12. 65
TL3	1.086	18.93
TL4	9.865	17.75
TL5	9.865	17.75
TL6	1.086	18.937
TL7	3.52	14.66
TL8	1.5	39.48
TL9	2.373	8.67
TL10	2.17	5.78
TL11	8.421	28.919
TL12	6.55	52.82
TL13	42.72	56.71
TL14	12.1	56.03
TL15	2.01	65.66
TL16	2.02	41.9
TL17	9.29	8.85

Figure 5: Overall schematic of the designed active antenna

TABLE 3: INDUCTANCE, CAPACITANCE AND RESISTANCE VALUES OF THE ACTIVE PART

Rs ohm	Ls nH	Rg ohm	Lg nH	Rd ohm	Ld nH	R1 ohm	R2 ohm	Vdc1 volt	Vdc2 volt	C_{GS} pf	C_{GD} pf	C_{DS} pf
0.06	0.1	6	0.72	6	0.68	150	150	-0.48	2	0.04	0.001	0.035

Another remarkable point here is the amount of power which is given to the patch antenna. If a source with -10 dBm power at the frequency of 3 GHz is injected at the input port of active and passive antenna, the amount of power which is delivered to the patch antenna in active case is 10.795 dB more than the delivered power in the passive one (Fig. 7). This amount of increased output power in active antenna is due to the applied amplifier between the input port and patch antenna. This indicates that by applying the same amount of input power to active and passive antennas, the active one would be able to produce more output power. This amount of increased output power in active antennas makes them suitable for transmitting applications
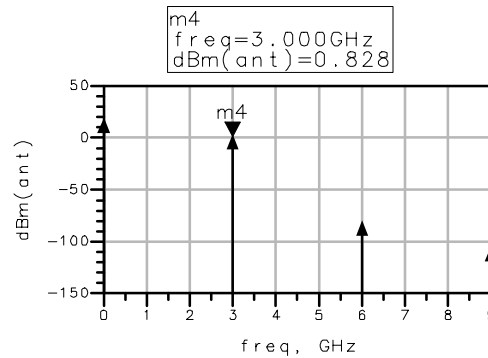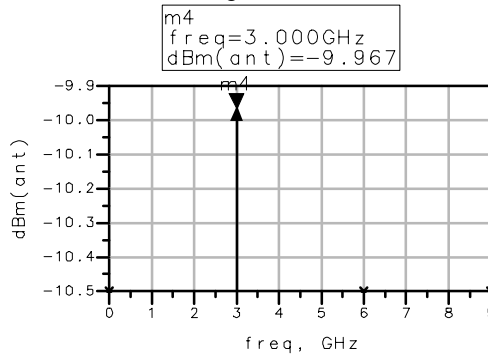

Figure 7-a

Figure 7-b

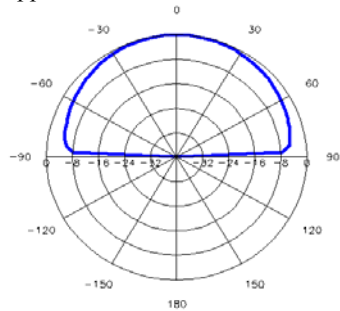Figure 7: The delivered power (in dBm) to the patch antenna in active (7-a) and passive (7-b) cases

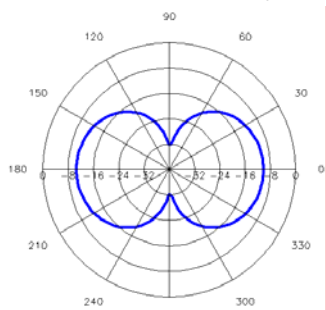
Fig 6-a: E field pattern in ϕ=0

Fig 6-b: E field pattern in θ=90

Figure 6: E_θ and E_φ patterns of passive Antenna

4. CIRCUIT ANALYSIS

A. Harmonic Balance Technique

For analyzing the circuit we first separate the linear and nonlinear elements in two subcircuits in HB method (Fig. 8). The time-domain approach is used for analyzing the nonlinear section and the frequency domain approach for the linear section [12], [13].

The aim of analysis is to obtain the ports voltages so that the sum of linear and nonlinear currents at each port becomes zero. Having the frequency-domain port voltages, and using the Y-parameter matrix of the linear subcircuit, the port currents can be easily found.

By inverse Fourier transforming of the voltages and using the device equations, the port currents in time domain can be obtained. The main idea can be shown with a KCL equation:

$$I + \hat{I} = 0 \qquad (9)$$

where I and $\hat{I}$ are the linear and nonlinear current vectors at each port between the two subcircuits:
$$I = \begin{bmatrix} I_{1,0} & I_{1,1} & . & . & I_{1,K} & I_{2,0} & I_{2,1} & . & I_{2,K} & . & I_{N,K} \end{bmatrix}$$
in which N is the number of common ports between linear and nonlinear subcircuits and K is the number of harmonics.

The current-voltage equation of linear part at internal ports is:

$$I = \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} Y_{13} & Y_{14} & Y_{15} \\ Y_{23} & Y_{24} & Y_{25} \end{bmatrix} \begin{bmatrix} V_3 \\ V_4 \\ V_5 \end{bmatrix} + \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \qquad (10)$$

and the admittance matrix of the linear network is obtained by the ADS simulator.. Also, the current vector of nonlinear subcircuit is given by equation (11), in which I_{ds} is the nonlinear current source and Q_{Cgs} is the charge vector of the nonlinear capacitance. Ω is a diagonal matrix in which the main diagonal has N cycles of $(0, 1, 2...K-1, K)\ \omega_p$.

$$\hat{I} = \begin{bmatrix} \hat{I}_{1,0} \\ \hat{I}_{1,1} \\ ... \\ \hat{I}_{1,K} \\ \hat{I}_{2,0} \\ ... \\ I_{2,K} \end{bmatrix} = \begin{bmatrix} 0 \\ .. \\ 0 \\ 0 \\ \hat{I}_{ds,0} \\ ... \\ \hat{I}_{ds,K} \end{bmatrix} + j\Omega_{2(K+1)*2(K+1)} \begin{bmatrix} Q_{gs,0} \\ Q_{gs,1} \\ ... \\ Q_{gs,K} \\ 0 \\ ... \\ 0 \end{bmatrix} \qquad (11)$$

Finally the current-error vector can be expressed as:

$$F(V) = Y_s.V_s + Y_{N*N}.V + I_G(V) + j\Omega Q(V) = 0 \qquad (12)$$

where V_s is the voltage vector of the sources and Y_s is the admittance matrix of the linear subcircuit related to voltage sources. This represents an equation that can be solved for the port voltage vector. (V)

B. Solving HB Equation by Splitting Algorithm

In splitting algorithm, we begin with a suitable estimation of the voltage vector and call it V^0. If we have the frequency-components of V^0, by the inverse Fourier transforming of these components and putting them in nonlinear characteristics, the nonlinear current vector, $\hat{I}^0$, can be found. Then, we assume $I^0 = -\hat{I}^0$, in which I^0 is the first estimation of linear current vector. Using the matrix

admittance of linear subcircuit, the new voltage vector, V, is obtained as:

$$V' = Z_{(N*N)}(I^0 - I_s)$$
$$Z_{(N*N)} = Y_{(N*N)}^{-1} \qquad (13)$$

We finally estimate the new voltage vector as given below.

$$V'' = sV' + (1-s)V^0; \quad 0 < s < 1 \qquad (14)$$

in which s is a real constant such that if it approaches 1, the convergence speed and instability will increase and if it approaches 0, the convergence speed and instability will decrease. So we should do a trade off between stability and convergence speed by an appropriate selection of s. we solves iterative harmonic balance equation until the convergence with the desired resolution is obtained.

C. Active Antenna Analysis by Harmonic Balance Approach

In the analysis of active antenna, the circuit is excited with an external power source at the frequency of 3 GHz. The number of harmonics is considered 2, $(K=2)$, so there are a DC component and two first harmonics of fundamental frequency in the analysis with HB method. In splitting algorithm, this is used for finding unknown terminal voltages. The s coefficient sets to 0.05.

After 1000 iterations, the absolute magnitude of current-error vector components reaches in the order of 10^{-15}, which is adequate enough to guarantee the accuracy of the HB analysis. The time-domain terminal voltages, V_1 and V_2, which are obtained by applying HB approach, also are simulated with commercial software. These voltages have been shown in Fig. 9. The slight difference between simulated voltages with commercial software and Matlab is due to neglecting Gate-Drain capacitance in the nonlinear model and accuracy of Cubic Curtice relations which are used in the harmonic balance analysis.

5. CONCLUSION

The Harmonic Balance method has been used for nonlinear analysis of the active antenna. In this approach we employed the large-signal model for the transistor used in the amplifier. Also the finite difference time-domain method has been applied to the analysis of the patch antenna which is used as load of the amplifier. The computed return loss obtained by the FDTD method has been found in a good agreement with that of the Momentum, which is a commercial software. Finally, the steady-state terminal voltages at common ports between linear and nonlinear parts of the active antenna have been obtained with HB approach, which show a good match with those obtained by the commercial softwares.
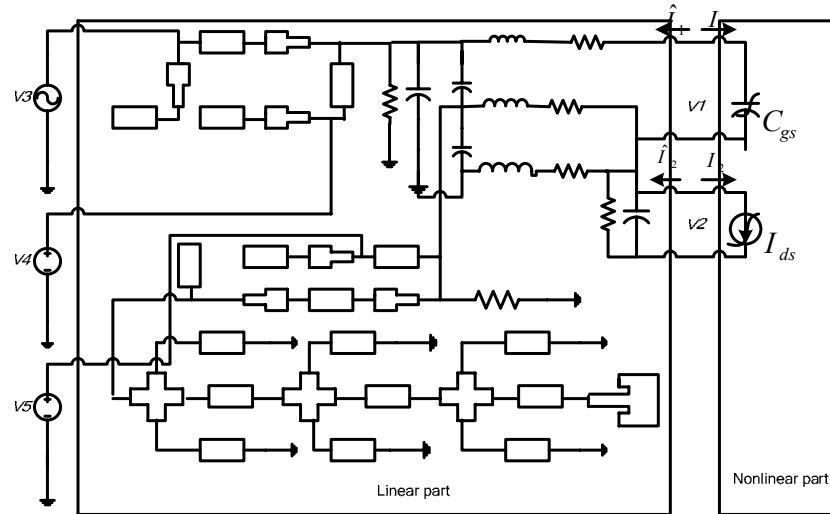
Figure 8: Linear and Nonlinear Sections of Active Antenna
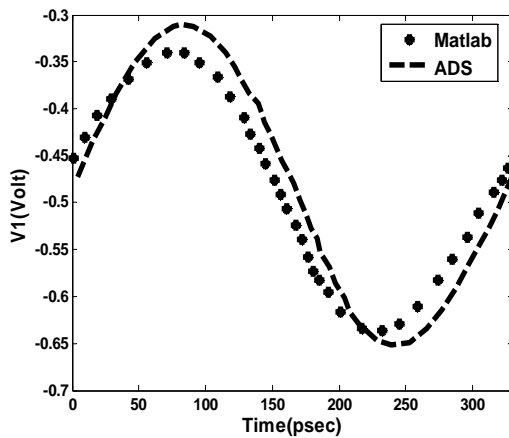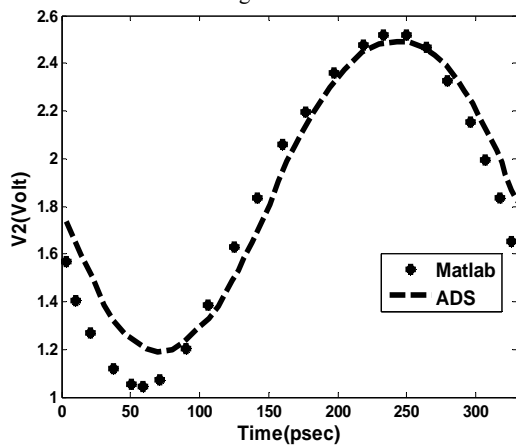

Figure 9-a

Figure 9-b

Figure 9: Terminal voltages, V1 and V2 (volt)

below in which V_1 and V_2 are common voltages between linear and nonlinear part, $V3$ is the input excitation voltage and V_4 and V_5 are bias source voltages employed in the input and output matching networks, respectively.

$$
\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} & Y_1 \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} & Y_{25} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} & Y_{35} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} & Y_{45} \\ Y_{51} & Y_{52} & Y_{53} & Y_{54} & Y_{55} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \end{bmatrix}
$$

Also by converting external voltage sources to short circuit and considering their effects as current sources at the internal ports, equation (10) can be obtained, in which V_n and $Y_{m,n}$ is shown as:

$$
Y_{m,n} = diag\left[Y_{m,n}(K\omega_p) \right]; \qquad k = 0, 1, 2 ...
$$

$$
V_n = \begin{bmatrix} V_{n,0} & V_{n,1} & V_{n,2} & . & V_{n,K} \end{bmatrix}
$$

Therefore the current- voltage relation of linear part can be expressed as the following equation:

$$
\begin{bmatrix} I_{1,0} \\ I_{1,1} \\ . \\ I_{1,K} \\ I_{2,0} \\ . \\ I_{2,K} \\ . \\ I_{5,K} \end{bmatrix} = \begin{bmatrix} Y_{1,1}(0) & 0 & ... & 0 & ... & Y_{1,5}(0) & 0 & ... & 0 \\ 0 & Y_{1,1}(\omega_P) & ... & 0 & ... & 0 & Y_{1,5}(\omega_P) & ... & 0 \\ ... & 0 & ... & & ... & ... & ... & ... & ... \\ 0 & 0 & ... & Y_{1,1}(K\omega_P) & ... & 0 & 0 & ... & Y_{1,5}(K\omega_P) \\ ... & ... & ... & ... & ... & ... & ... & ... & ... \\ Y_{5,1}(0) & 0 & ... & 0 & ... & Y_{5,5}(0) & 0 & ... & 0 \\ 0 & Y_{5,1}(\omega_P) & ... & 0 & ... & 0 & Y_{5,5}(\omega_P) & ... & 0 \\ ... & 0 & ... & ... & ... & ... & 0 & ... & ... \\ 0 & 0 & ... & Y_{5,1}(K\omega_P) & ... & 0 & 0 & ... & Y_{5,5}(K\omega_P) \end{bmatrix} \begin{bmatrix} V_{1,0} \\ V_{1,1} \\ ... \\ V_{1,K} \\ V_{2,0} \\ ... \\ V_{2,K} \\ ... \\ V_{5,K} \end{bmatrix}
$$

6. APPENDIX

Here is a brief explanation of equation (10). The current- voltage relation of linear part can be shown as

7. ACKNOWLEDGMENT

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